

AD-A138 768

EFFECT OF INTERFACIAL BONDING ON THE STRENGTH OF
ADHESION OF ELASTOMERS I. (U) AKRON UNIV OH INST OF
POLYMER SCIENCE A N GENT ET AL. FEB 84 TR-38

1/1

UNCLASSIFIED

N00014-76-C-0408

F/G 20/11

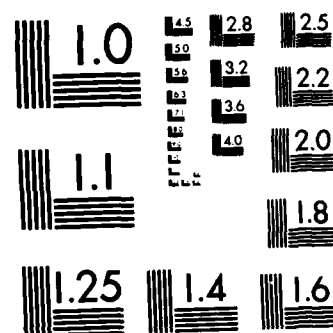
NL

END

1-1000

64

DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

12

OFFICE OF NAVAL RESEARCH

Contract N00014-76-C-0408

Project NR 092-555

Technical Report No. 30

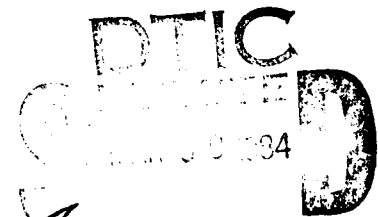
EFFECT OF INTERFACIAL BONDING ON THE STRENGTH OF
ADHESION OF ELASTOMERS III. INTERLINKING
BY MOLECULAR ENTANGLEMENTS

by

A. N. Gent and R. H. Tobias

Institute of Polymer Science
The University of Akron
Akron, Ohio 44325

February, 1984



Reproduction in whole or in part is permitted
for any purpose of the United States Government

Approved for Public Release; Distribution Unrestricted

AD A138760

DTIC FILE COPY

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM	
1. REPORT NUMBER Technical Report 30	2. GOVT ACCESSION NO. AD A138 760	3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Effect of Interfacial Bonding on the Strength of Adhesion of Elastomers. III. Interlinking by Molecular Entanglements		5. TYPE OF REPORT & PERIOD COVERED Technical Report	
		6. PERFORMING ORG. REPORT NUMBER	
7. AUTHOR(s) A. N. Gent and R. H. Tobias		8. CONTRACT OR GRANT NUMBER(s) N00014-76-C-0408	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Institute of Polymer Science The University of Akron Akron, Ohio 44325		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 092-555	
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Power Program Arlington, VA 22217		12. REPORT DATE February, 1984	
		13. NUMBER OF PAGES 25	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified	
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
16. DISTRIBUTION STATEMENT (of this Report) According to attached distribution list. Approved for public release; distribution unrestricted			
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)			
18. SUPPLEMENTARY NOTES submitted to J. Polym. Sci.: Polym. Phys. Ed.			
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) adhesion, diffusion, endlinked polydimethylsiloxane, elastomers, interfacial bonding, interlinking by entanglement, Lake and Thomas theory, molecular entanglements, polydimethylsiloxane, separation at threshold conditions, strength of adhesion, work of detachment			
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Polydimethylsiloxane (PDMS) networks have been formed by endlinking linear PDMS molecules. When a second layer is cast on top of a fully-gelled lower layer, the new molecules diffuse into the surface of the lower layer and form molecular loops (entanglements) in the course of endlinking with themselves. The two layers are then joined only by these macromolecular loops. Measurements have been made of the work required to separate such layers under threshold conditions, i.e., at low rates, high temperatures, and, in some cases, in the swollen state. Values of the work of detachment have been			

found to be $15-25 \text{ J/m}^2$, generally about one-half of the work of fracture of the layers themselves, and consistent with the inferred density of interlinking molecular loops at the interface. The values were higher for higher densities, roughly in proportion, and for interlinking molecular strands of higher molecular weight, in accordance with the theory of Lake and Thomas. In the absence of interlinking the work of detachment was extremely small, only about 70 mJ/m^2 .

Accession For	
LTIS COPY	X
REF ID	
Unrec'd	
Jan 1961	
By	
Digitized	
Approved for Release	
Dist	SP-1

A-1
OTIC
COPY
INSPECTION

SUMMARY

Polydimethylsiloxane (PDMS) networks have been formed by endlinking linear PDMS molecules. When a second layer is cast on top of a fully-gelled lower layer, the new molecules diffuse into the surface of the lower layer and form molecular loops ("entanglements") in the course of endlinking with themselves. The two layers are then joined only by these macromolecular loops. Measurements have been made of the work required to separate such layers under threshold conditions, i.e., at low rates, high temperatures, and, in some cases, in the swollen state. Values of the work of detachment have been found to be 15-25 J/m², generally about one-half of the work of fracture of the layers themselves, and consistent with the inferred density of interlinking molecular loops at the interface. The values were higher for higher densities, roughly in proportion, and for interlinking molecular strands of higher molecular weight, in accordance with the theory of Lake and Thomas. In the absence of interlinking the work of detachment was extremely small, only about 70 mJ/m².

INTRODUCTION

Measurements are reported here of the mechanical strength of molecular networks formed by the physical entanglement of elastomeric macromolecules. Previous studies have focussed on networks formed by interlinking macromolecules by covalent bonds (1-3). Such networks are relatively strong even under

threshold conditions, when dissipative processes are minimized. The work G_c of fracture per unit area torn through is then about 30-100 J/m², large in comparison with the theoretical value for a plane of C-C covalent bonds, about 1 J/m². This difference has been attributed by Lake and Thomas to the polymeric nature of the molecular strands comprising the network: many bonds must be stressed in order to break any strand (4). They concluded that the work of fracture is given by

$$G_c = K M_c^{\frac{1}{2}} \quad (1)$$

where M_c is the molecular weight of a network strand and K is a constant involving the density of the polymer, the effective mass, length and flexibility of a single main-chain bond, and the bond dissociation energy.

In Part I (5), two sheets of a crosslinked elastomer were placed in contact and joined by covalent chemical bonds. The work G_a of detachment under threshold conditions was found to increase in proportion to the density of interfacial bonds, from the low value characteristic of only Van der Waals' attractions up to the work G_c of fracture of the sheets themselves. Again, for a given density of interfacial interlinking the detachment work G_a was found to be greater when the network and interlinking strands were longer, in accordance with the concept of Lake and Thomas (5,6).

We now address the question: suppose two elastomeric sheets are connected together by molecules which loop around others in the opposite surface, forming permanent molecular

"entanglements", but are not connected directly by interlinking bonds, will the strength of adhesion be substantially different from the covalently-bonded case? The answer will be important for any quantitative treatment of the relationship between network structure and threshold strength.

The method employed for preparing pairs of elastomeric sheets joined only by "entanglements" was as follows. A layer of end-linkable polydimethylsiloxane (PDMS) linear polymer was poured as a flat sheet and then subjected to an end-linking (gelation) reaction using a tetrafunctional silane linking reagent (3,7). On top of the elastomeric PDMS sheet prepared in this way a second layer of PDMS polymer was poured and gelled in situ. Because the first layer was completely reacted, the second layer was unable to link with it directly. But, because of the relatively rapid interdiffusion of PDMS molecules (8), there will be a substantial penetration of the first layer by molecules of the second while they are in the process of end-linking to form the second elastomeric layer. Thus, the two layers will be joined by a permanent molecular entanglement wherever a molecule of the second layer loops around one of the first layer before end-linking is complete, Figure 1.

Values of the detachment work G_a per unit area of interface have been determined for sheets interlinked in this way. They are reported here for specimens prepared using PDMS of three different molecular weights, and they are compared with corresponding values for unentangled sheets, held together only by Van der Waals attractions.

EXPERIMENTAL DETAILS

(i) Preparation of polydimethylsiloxane (PDMS) networks

Networks were prepared as described elsewhere (3) from linear polydimethylsiloxanes having vinyl end groups. A tetrafunctional silane linking agent, tetrakisdimethylsiloxysilane, kindly supplied by Prof. C. W. Macosko, was mixed with the divinyl polymer, together with about 5 ppm of a Pt catalyst (9). The mixture was then degassed and cast as a thin sheet, about 1 mm thick, on a Teflon surface. Complete reaction, judged by the attainment of minimum swelling of the resultant gel in benzene, was achieved after 3 days at 70°C. Test sheets were therefore prepared by heating for 4 days at 70°C to ensure complete reaction.

Polymers having three different molecular weight ($\bar{M}_n = 11,500, 22,500$ and $36,000$ g/g-mole) were used for preparing networks. GPC data gave values for the ratio \bar{M}_w/\bar{M}_n of each polymer of approximately 2.0.

(ii) Preparation of interlinked layers

Samples were made by first casting one layer of endlinked PDMS, as described above, and then casting a second layer on top of it. In some cases the upper surface of the first layer was treated with 1-nonene and a small amount of a Pt catalyst (5 ppm) to saturate any residual SiH groups in the surface and thus prevent any possible chemical linking between the two layers. The top layer was then cast on in the usual way. No difference

was observed in the strength of adhesion for treated and untreated samples. It was concluded that no chemical linking occurred when the first layer was cured for 4 days at 70°C before the second layer was applied.

(iii) Measurement of the threshold work G_a of detachment

Measurements were made of the peel force required to separate two adhering layers, Figure 2. Samples were pre-swollen with m-xylene or silicone oil in some instances and immersed in a water bath at temperatures between 70°C and 90°C. The water effectively prevented evaporation of the swelling liquid. Only "symmetrical" samples were tested in the swollen state. "Symmetrical" samples are those in which both layers were made from PDMS of the same molecular weight, so that the crosslink density was the same and the degree of swelling would be equal. Values of the work G_a of detachment were then calculated from the measured peel force P per unit width:

$$G_a = 2\lambda_s^2 P \quad (2)$$

where λ_s is the linear swelling ratio. The term λ_s^2 in equation 2 accounts for the reduced number of network strands crossing the interface in a swollen specimen. For unswollen specimens, $\lambda_s = 1$.

Peeling was carried out in all cases at a rate of about 8 $\mu\text{m/s}$.

In order to study the strength of adhesion due to dispersion forces alone, thin sheets about 0.8 mm thick were cast and placed in contact with each other after cure. The upper surfaces of

cast sheets were smooth and shiny, and were brought into contact for these experiments. No difference was found in the measured peel force after 15 min and 24 h of contact. Therefore, 15 min was adopted as a standard contact time. Peeling separation was then carried out at room temperature at a rate of about 8 $\mu\text{m}/\text{s}$.

One pair of sheets was extracted with benzene at room temperature in an attempt to remove low-molecular-weight PDMS, inherent in PDMS materials. These samples gave the same (low) values of $\underline{G_a}$ as unextracted ones, 60-100 mJ/m^2 (Table 1). It is concluded that the strength of self-adhesion of PDMS materials under threshold conditions is extremely low, much lower than that observed previously for hydrocarbon elastomers, about 1 J/m^2 (5, 10). Possible reasons for this are discussed later.

RESULTS AND DISCUSSION

Values of $\underline{G_a}$ were measured for symmetrical interlinked specimens, both swollen and unswollen. They are given in Table 2. They were found to be in good agreement, when the factor λ_s^2 was employed to correct for changes in the interlinking density, and independent of the swelling liquid used. This agreement shows that threshold conditions had, indeed, been attained at the low rate of peel, 8 $\mu\text{m}/\text{s}$, and high temperatures, 70-90°C, used for these experiments.

Values of $\underline{G_a}$ for all of the interlinked samples are given in Table 3. They varied from 15 to 25 J/m^2 , depending upon

the molecular weights of the PDMS liquids used in preparing the top and bottom layers. When these molecular weights were both low, then the strength of adhesion was relatively low, and when they were higher, then the strength of adhesion was relatively high. This trend is consistent with previous results for the strength of adhesion of elastomer layers to each other (5) and to glass (10) and for their cohesive strengths also (2, 3, 6). In all cases, the work of fracture was greater when the network strands were longer, as predicted by Lake and Thomas (4). For the present materials, the network strand molecular weight is given by the molecular weight of the precursor polymer, to a first approximation.

In one case the upper layer could not be detached cleanly. It tore apart, requiring the input work $\underline{G_c}$ of cohesive rupture, instead of detaching. Molecules of the second layer had apparently penetrated the first layer to such an extent in this case that the interface was no longer the weakest plane. In all other cases, however, the work $\underline{G_a}$ of detachment was considerably smaller than the work $\underline{G_c}$ of cohesive rupture of either of the two adhering layers. Values of $\underline{G_c}$, taken from reference 3, are given in parentheses in Table 3, for comparison.

It is assumed that polymer molecules of the upper layer diffuse rapidly into the already-gelled lower layer and reach an equilibrium concentration in the surface regions quickly, before they undergo a significant amount of end-linking and gelation. Measurements of the equilibrium uptake of PDMS

liquids by PDMS gels have been reported previously (8). The results are given in Table 4 for the systems studied here. They range from 11 to 57 per cent uptake of the liquid by unit volume of the gel.

On comparing Tables 3 and 4, a general correlation is evident between the threshold work \underline{G}_a of detachment and the amount of PDMS liquid taken up at equilibrium, for each liquid. In Figure 3, values of \underline{G}_a are plotted against the volume uptake \underline{c} . They are seen to be described reasonably well by linear relations for each PDMS liquid forming the upper layer on later gelation. Thus, it appears that the strength of adhesion of the upper layer is approximately proportional to the amount of the precursor liquid absorbed by the lower layer, and hence to the number of interlinking strands. Moreover, the slopes of the linear relations shown in Figure 4 between \underline{G}_a and \underline{c} ; i.e., 60, 90 and 135 J/m²; are approximately in proportion to values of $\underline{M}_n^{1/2}$ for the PDMS liquid in the upper layer, which are in the ratio 65:90:115. Thus, the lengths of the interlinking strands also determine the strength of adhesion, in good quantitative agreement with the Lake-Thomas theory.

The horizontal broken lines in Figure 4 denote the work \underline{G}_c of cohesive rupture for each upper layer. By extrapolation in two cases, and by direct observation in the third, it is concluded that when the density of interlinking strands exceeds 35-50 per cent of those present in the lower layer then clean separation at the interface is no longer the clearly-preferred

mode of fracture. At this stage, the total density of chains crossing the interfacial plane will be about twice as large, 70-100 per cent, assuming that each pair of strands from the upper layer interlink successfully with a network mesh in the lower layer, so that the number of interlinking strands approaches that for a randomly-chosen plane within the upper or lower layer. It is not surprising, therefore, that cohesive rupture replaces interfacial separation at this point.

Finally, reference should be made to the extraordinarily low values obtained for adhesion between non-interlinked sheets, Table 1, in comparison with those obtained previously for the adhesion of sheets of hydrocarbon elastomers, about 1 J/m^2 (5). The present results are much closer to theoretical values for the maximum work of detachment due to Van der Waals' attractions alone, given by $2S$ where S is the surface energy of the elastomer layer. Thus, G_a is expected to fall in the range $40\text{-}80 \text{ mJm}^2$ on this basis, in good agreement with the present values for PDMS sheets.

However, it was found previously that other elastomeric materials adhere together much more strongly, and this was attributed to a generalization of the mechanism proposed by Lake and Thomas to account for their higher cohesive strength: that many bonds in a network strand must be stressed in order to break any one of them (5, 10). In the case of autohesion, the bond to be broken is the weak Van der Waals association at the interface, but the principle should still hold that the same

energy must be imparted to every bond in the molecular chain leading from the interface to the network itself, in order to break the association.

The question is, therefore: Are the present results representative of elastomeric materials in general, with the previous results for hydrocarbon elastomers anomalously high? Or, are the previous results representative of elastomeric materials in general, and the present results for PDMS layers anomalously low?

Extraction of PDMS sheets with benzene did not raise the level of adhesion significantly. Thus, there does not appear to be a liquid-like layer on the surface, responsible for low self-adhesion. On the other hand, it is extremely difficult to remove low-molecular-weight silicone fluids completely. The question raised above must therefore be considered unresolved, at present. It merits further study, in view of the large differences, by a factor of 10-20, between the two systems, and the theoretical and practical importance of the self-adhesion of elastomeric materials.

CONCLUSIONS

The main conclusion is that permanently "entangled" macromolecular loops appear to have about the same strength as covalently-bonded macromolecules of the same length. A second conclusion is that the work of rupture across a plane of such entanglements is roughly proportional to the inferred

density of entanglement interlinking. And, finally, the greater the molecular weight of the molecular strands comprising the loops, the greater appears to be the work of rupture, in accord with the theoretical treatment of Lake and Thomas for the cohesive strength of an elastomeric network. These conclusions have clear implications for the strength of molecular networks containing trapped entanglements.

REFERENCES

1. H. K. Mueller and W. G. Knauss, Trans. Soc. Rheol., 15, 217-233 (1971).
2. A. Ahagon and A. N. Gent, J. Polym. Sci. Polym. Phys. Ed., 13, 1903-1911 (1975).
3. A. N. Gent and R. H. Tobias, J. Polym. Sci. Polym. Phys. Ed., 20, 2051-2058 (1982).
4. G. J. Lake and A. G. Thomas, Proc. Roy. Soc. Lond., A300 108-119 (1967).
5. R. J. Chang and A. N. Gent, J. Polym. Sci. Polym. Phys. Ed., 19, 1619-1633 (1981).
6. A. K. Bhowmick and A. N. Gent, submitted to Rubber Chem. Technol.
7. E. M. Valles and C. W. Macoski. Rubber Chem. Technol., 49, 1232-1237 (1976).
8. A. N. Gent and R. H. Tobias, J. Polym. Sci. Polym. Phys. Ed., 20, 2317-2327 (1982).
9. C. B. Kauffman and D. O. Cowan, in "Inorganic Synthesis", Vol. 6, E. G. Rochow, Ed., McGraw-Hill, N.Y. 1969, Chap. VIII.
10. A. Ahagon and A. N. Gent, J. Polym. Sci. Polym. Phys. Ed., 13, 1285-1300 (1975).

Table 1. Work G_a (mJ/m²) of detachment for
fully-cured PDMS layers, placed in contact

		Molecular weight \bar{M}_n of PDMS in upper layer		
		11,500	22,500	36,000
\bar{M}_n in lower layer	11,500	66 ± 3	60 ± 4	81 ± 2
	22,500	60 ± 4	80 ± 3	84 ± 2
	36,000	81 ± 2	84 ± 2	97 ± 4

Table 2. Threshold work $\underline{G_a}$ of detachment for
unswollen and swollen interlinked PDMS layers

Molecular weight $\underline{M_n}$ of PDMS in both layers

	11,500	22,500	36,000
Unswollen			
G_a (J/m ²)	14.5±0.8	19.5±1.5	24.9±1.4
Swollen in m-xylene			
λ_s	1.51	1.57	1.67
2P (N/m)	7.4±0.7	8.3±0.5	9.5±0.5
G_a (J/m ²) *	16.8±1.4	20.5±1.2	26.4±1.2
Swollen in silicone oil			
λ_s	1.19	1.24	1.30
2P (N/m)	10.5±1.3	12.7±0.9	14.7±0.8
G_a (J/m ²) *	14.7±1.7	19.6±1.4	24.8±1.3

$$* G_a = 2\lambda_s^2 P$$

Table 3. Threshold work G_a (J/m^2) of detachment for interlinked PDMS layers and threshold fracture energy G_c (J/m^2), in parentheses, for the layers themselves

		Molecular weight \bar{M}_n of PDMS in upper layer		
		11,500	22,500	36,000
\bar{M}_n in lower layer	11,500	15.5±0.4 (35)	17.1±0.4	18.9±0.5
	22,500	17.5±0.7	20.1±0.4 (44)	22.7±0.5
	36,000	(cohesive rupture)	24.6±0.6	25.6±0.4 (48)

Table 4. Volume of PDMS liquid taken up at equilibrium by unit volume of PDMS gels (taken from reference 8).

		Molecular weight \bar{M}_n of PDMS liquid		
		11,500	22,500	36,000
\bar{M}_n of PDMS gel	11,500	0.271	0.149	0.109
	22,500	0.375	0.220	0.162
	36,000	0.572	0.283	0.211

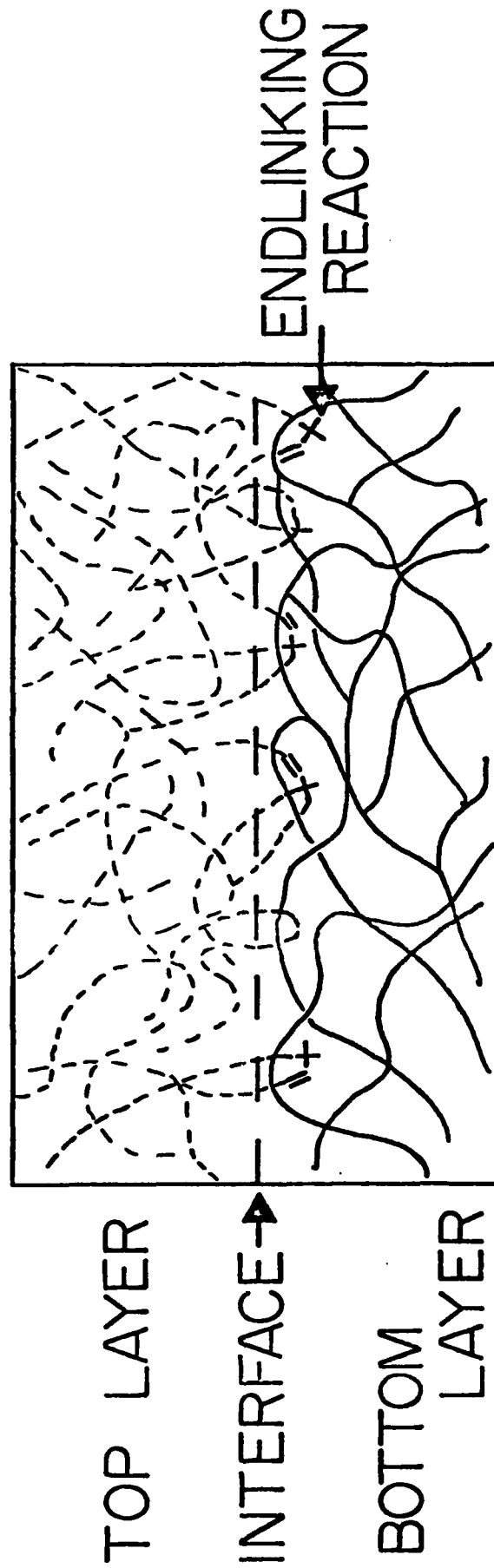


Figure 1. Sketch of the formation of macromolecular loops (permanent "entanglements") between an initially-gelled lower layer and an upper layer, applied and gelled later by an end-linking reaction.

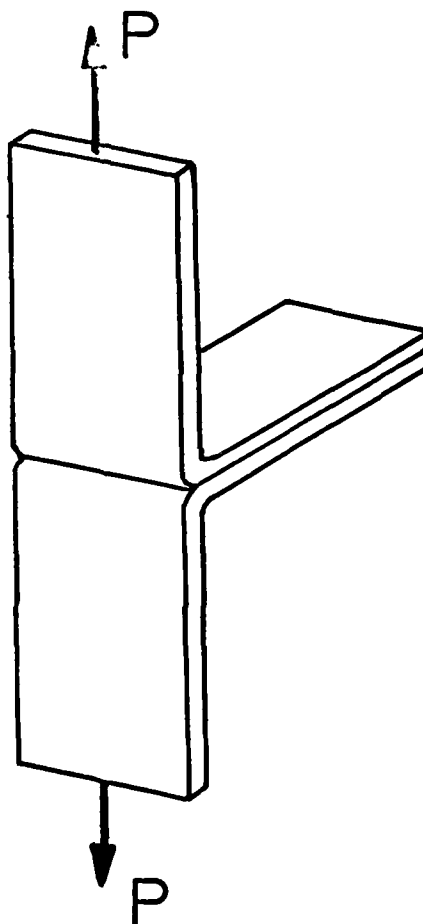


Figure 2. Method employed for measuring the work G_a of detachment. $G_a = 2P$, where \underline{P} is \underline{a} the peel force per unit width.

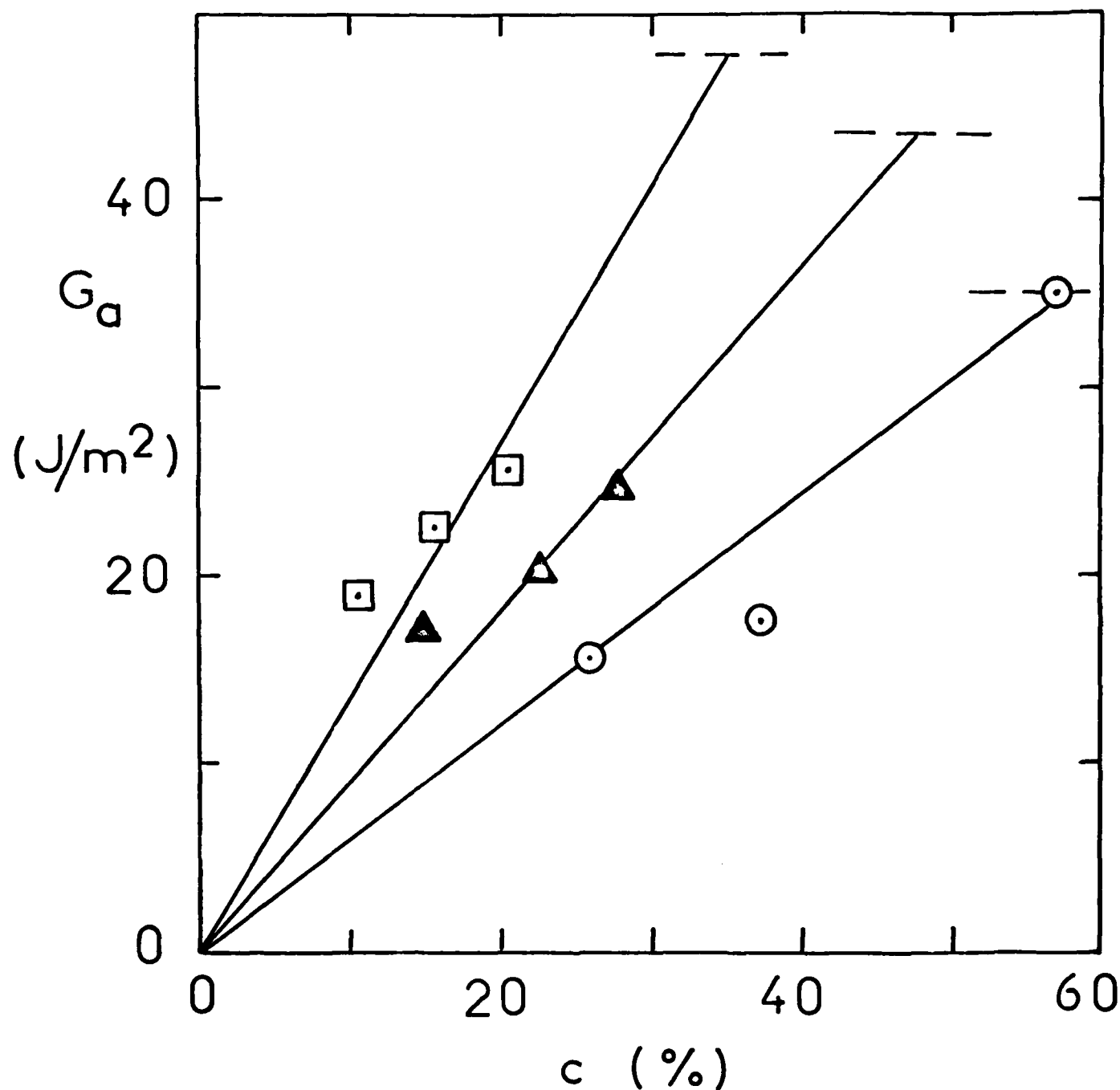


Figure 3. Relations between the work G_a of detachment of a PDMS layer and the concentration c of PDMS molecules absorbed by the lower layer before the upper layer was gelled. The horizontal broken lines denote the work G_c of fracture of the upper layer, after gelation. Molecular weight of PDMS used for the upper layer: 11,500, ○; 22,500, ▲; 36,000, ◻.

DISTRIBUTION LIST

	<u>No. Copies</u>		<u>No. Copies</u>
Dr. L.V. Schmidt Assistant Secretary of the Navy (R,E, and S) Room 5E 731 Pentagon Washington, D.C. 20350	1	Dr. F. Roberto Code AFRPL MKPA Edwards AFB, CA 93523	1
Dr. A.L. Slafkosky Scientific Advisor Commandant of the Marine Corps Code RD-1 Washington, D.C. 20380	1	Dr. L.H. Caveny Air Force Office of Scientific Research Directorate of Aerospace Sciences Bolling Air Force Base Washington, D.C. 20332	1
Dr. Richard S. Miller Office of Naval Research Code 413 Arlington, VA 22217	10	Mr. Donald L. Ball Air Force Office of Scientific Research Directorate of Chemical Sciences Bolling Air Force Base Washington, D.C. 20332	1
Mr. David Siegel Office of Naval Research Code 250 Arlington, VA 22217	1	Dr. John S. Wilkes, Jr. FJSRL/NC USAF Academy, CO 80840	1
Dr. R.J. Marcus Office of Naval Research Western Office 1030 East Green Street Pasadena, CA 91106	1	Dr. R.L. Lou Aerojet Strategic Propulsion Co. P.O. Box 15699C Sacramento, CA 95813	1
Dr. Larry Peebles Office of Naval Research East Central Regional Office 666 Summer Street, Bldg. 114-D Boston, MA 02210	1	Dr. V.J. Keenan Anal-Syn Lab Inc. P.O. Box 547 Paoli, PA 19301	1
Dr. Phillip A. Miller Office of Naval Research San Francisco Area Office One Hallidie Plaza, Suite 601 San Francisco, CA 94102	1	Dr. Philip Howe Army Ballistic Research Labs ARRADCOM Code ORDAR-BLT Aberdeen Proving Ground, MD 21005	1
Mr. Otto K. Heiney AFATL - DLJL Elgin AFB, FL 32542	1	Mr. L.A. Watermeier Army Ballistic Research Labs ARRADCOM Code ORDAR-BLI Aberdeen Proving Ground, MD 21005	1
Mr. R. Geisler ATTN: MKP/MS24 AFRPL Edwards AFB, CA 93523	1	Dr. W.W. Wharton Attn: DRSNI-RKL Commander U.S. Army Missile Command Redstone Arsenal, AL 35898	1

DISTRIBUTION LIST

	<u>No. Copies</u>		<u>No. Copies</u>
Dr. R.G. Rhoades Commander Army Missile Command DRSMI-R Redstone Arsenal, AL 35898	1	Dr. E.H. Debutts Hercules Inc. Baccus Works P.O. Box 98 Magna, UT 84044	1
Dr. W.D. Stephens Atlantic Research Corp. Pine Ridge Plant 7511 Wellington Rd. Gainesville, VA 22065	1	Dr. James H. Thacher Hercules Inc. Magna Baccus Works P.O. Box 98 Magna, UT 84044	1
Dr. A.W. Barrows Ballistic Research Laboratory USA ARRADCOM DRDAR-BLP Aberdeen Proving Ground, MD 21005	1	Mr. Theodore M. Gilliland Johns Hopkins University APL Chemical Propulsion Info. Agency Johns Hopkins Road Laurel, MD 20810	1
Dr. C.M. Frey Chemical Systems Division P.O. Box 358 Sunnyvale, CA 94086	1	Dr. R. McGuire Lawrence Livermore Laboratory University of California Code L-324 Livermore, CA 94550	1
Professor F. Rodriguez Cornell University School of Chemical Engineering Olin Hall, Ithaca, N.Y. 14853	1	Dr. Jack Linsk Lockheed Missiles & Space Co. P.O. Box 504 Code Org. 83-10, Bldg. 154 Sunnyvale, CA 94088	1
Defense Technical Information Center DTIC-DDA-2 Cameron Station Alexandria, VA 22314	12	Dr. B.G. Craig Los Alamos National Lab P.O. Box 1663 NSP/DOD, MS-245 Los Alamos, NM 87545	1
Dr. Rocco C. Musso Hercules Aerospace Division Hercules Incorporated Alleghany Ballistic Lab P.O. Box 210 Washington, D.C. 21502	1	Dr. R.L. Rabie WX-2, MS-952 Los Alamos National Lab. P.O. Box 1663 Los Alamos NM 87545	1
Dr. Ronald L. Simmons Hercules Inc. Eglin AFATL/DLJL Eglin AFB, FL 32542	1	Dr. B. Rogers Los Alamos Scientific Lab. P.O. Box 1663 Los Alamos, NM 87545	1

DISTRIBUTION LIST

	<u>No. Copies</u>		<u>No. Copies</u>
Mr. R. Brown Naval Air Systems Command Code 330 Washington, D.C. 20361	1	Dr. J. Schnur Naval Research Lab. Code 6510 Washington, D.C. 20375	1
Dr. H. Rosenwasser Naval Air Systems Command AIR-310C Washington, D.C. 20360	1	Mr. R. Beauregard Naval Sea Systems Command SEA 64E Washington, D.C. 20362	1
Mr. B. Sobers Naval Air Systems Command Code 03P25 Washington, D.C. 20360	1	Mr. G. Edwards Naval Sea Systems Command Code 62R3 Washington, D.C. 20362	1
Dr. L.R. Rothstein Assistant Director Naval Explosives Dev. Engineering Dept. Naval Weapons Station Yorktown, VA 23691	1	Mr. John Boyle Materials Branch Naval Ship Engineering Center Philadelphia, PA 19112	1
Dr. Lionel Dickinson Naval Explosive Ordnance Disposal Tech. Center Code D Indian Head, MD 20640	1	Dr. H.G. Adolph Naval Surface Weapons Center Code R11 White Oak Silver Spring, MD 20910	1
Mr. C.L. Adams Naval Ordnance Station Code PM4 Indian Head, MD 20640	1	Dr. T.D. Austin Naval Surface Weapons Center Code R16 Indian Head, MD 20640	1
Mr. S. Mitchell Naval Ordnance Station Code 5253 Indian Head, MD 20640	1	Dr. T. Hall Code R-11 Naval Surface Weapons Center White Oak Laboratory Silver Spring, MD 20910	1
Dr. William Tolles Dean of Research Naval Postgraduate School Monterey, CA 93940	1	Mr. G.L. Mackenzie Naval Surface Weapons Center Code R101 Indian Head, MD 20640	1
Naval Research Lab. Code 6100 Washington, D.C. 20375	1	Dr. K.F. Mueller Naval Surface Weapons Center Code R11 White Oak Silver Spring, MD 20910	1

DISTRIBUTION LIST

	<u>No. Copies</u>		<u>No. Copies</u>
Mr. J. Murrin Naval Sea Systems Command Code 62R2 Washington, D.C. 20362	1	Dr. A. Nielsen Naval Weapons Center Code 385 China Lake, CA 93555	1
Dr. D.J. Pastine Naval Surface Weapons Center Code R04 White Oak Silver Spring, MD 20910	1	Dr. R. Reed, Jr. Naval Weapons Center Code 388 China Lake, CA 93555	1
Mr. L. Roslund Naval Surface Weapons Center Code R122 White Oak, Silver Spring MD 20910	1	Dr. L. Smith Naval Weapons Center Code 3205 China Lake, CA 93555	1
Mr. M. Stosz Naval Surface Weapons Center Code R121 White Oak Silver Spring, MD 20910	1	Dr. B. Douda Naval Weapons Support Center Code 5042 Crane, Indiana 47522	1
Dr. E. Zimmet Naval Surface Weapons Center Code R13 White Oak Silver Spring, MD 20910	1	Dr. A. Faulstich Chief of Naval Technology MAT Code 0716 Washington, D.C. 20360	1
Dr. D. R. Derr Naval Weapons Center Code 388 China Lake, CA 93555	1	LCDR J. Walker Chief of Naval Material Office of Naval Technology MAT, Code 0712 Washington, D.C. 20360	1
Mr. Lee N. Gilbert Naval Weapons Center Code 3205 China Lake, CA 93555	1	Mr. Joe McCartney Naval Ocean Systems Center San Diego, CA 92152	1
Dr. E. Martin Naval Weapons Center Code 3858 China Lake, CA 93555	1	Dr. S. Yamamoto Marine Sciences Division Naval Ocean Systems Center San Diego, CA 91232	1
Mr. R. McCarten Naval Weapons Center Code 3272 China Lake, CA 93555	1	Dr. G. Bosmajian Applied Chemistry Division Naval Ship Research & Development Center Annapolis, MD 21401	1
		Dr. H. Shuey Rohn and Haas Company Huntsville, Alabama 35801	1

DISTRIBUTION LIST

	<u>No. Copies</u>		<u>No. Copies</u>
Dr. J.F. Kincaid Strategic Systems Project Office Department of the Navy Room 901 Washington, D.C. 20376	1	Dr. C.W. Vriesen Thickol Elkton Division P.O. Box 241 Elkton, MD 21921	1
Strategic Systems Project Office Propulsion Unit Code SP2701 Department of the Navy Washington, D.C. 20376	1	Dr. J.C. Hinshaw Thickol Wasatch Division P.O. Box 524 Brigham City, Utah 84302	1
Mr. E.L. Throckmorton Strategic Systems Project Office Department of the Navy Room 1043 Washington, D.C. 20376	1	U.S. Army Research Office Chemical & Biological Sciences Division P.O. Box 12211 Research Triangle Park NC 27709	1
Dr. D.A. Flanigan Thickol Huntsville Division Huntsville, Alabama 35807	1	Dr. R.F. Walker USA ARRADCOM ORDAR-LCE Dover, NJ 07801	1
Mr. G.F. Mangum Thickol Corporation Huntsville Division Huntsville, Alabama 35807	1	Dr. T. Sinden Munitions Directorate Propellants and Explosives Defence Equipment Staff British Embassy 3100 Massachusetts Ave. Washington, D.C. 20003	1
Mr. E.S. Sutton Thickol Corporation Elkton Division P.O. Box 241 Elkton, MD 21921	1	LTC B. Loving AFROL/LK Edwards AFB, CA 93523	1
Dr. G. Thompson Thickol Wasatch Division MS 240 P.O. Box 524 Brigham City, UT 84302	1	Professor Alan N. Gent Institute of Polymer Science University of Akron Akron, OH 44325	1
Dr. T.F. Davidson Technical Director Thickol Corporation Government Systems Group P.O. Box 5253 Ogden, Utah 84409	1	Mr. J. M. Frankie Army Ballistic Research Labs ARRADCOM Code ORDAR-BLI Aberdeen Proving Ground, MD 21005	1

DISTRIBUTION LIST

<u>No. Copies</u>		<u>No. Copies</u>	
1	Dr. Ingo W. May Army Ballistic Research Labs ARRADCOM Code DRDAR-BLI Aberdeen Proving Ground, MD 21005	1	Dr. J. P. Marshall Dept. 52-35, Bldg. 204/2 Lockheed Missile & Space Co. 3251 Hanover Street Palo Alto, CA 94304
1	Professor N.W. Tschoegl California Institute of Tech Dept. of Chemical Engineering Pasadena, CA 91125	1	Ms. Joan L. Janney Los Alamos National Lab Mail Stop 920 Los Alamos, NM 87545
1	Professor M.D. Nicol University of California Dept. of Chemistry 405 Hilgard Avenue Los Angeles, CA 90024	1	Dr. J. M. Walsh Los Alamos Scientific Lab Los Alamos, NM 87545
1	Professor A. G. Evans University of California Berkeley, CA 94720	1	Professor R. W. Armstrong Univ. of Maryland Department of Mechanical Eng. College Park, MD 20742
1	Professor T. Litovitz Catholic Univ. of America Physics Department 520 Michigan Ave., N.E. Washington, D.C. 20017	1	Prof. Richard A. Reinhardt Naval Postgraduate School Physics & Chemistry Dept. Monterey, CA 93940
1	Professor W. G. Knauss Graduate Aeronautical Lab California Institute of Tech. Pasadena, CA 91125	1	Dr. R. Bernecker Naval Surface Weapons Center Code R13 White Oak, Silver Spring, MD 20910
1	Professor Edward Price Georgia Institute of Tech. School of Aerospace Engin. Atlanta, Georgia 30332	1	Dr. M. J. Kamlet Naval Surface Weapons Center Code R11 White Oak, Silver Spring, MD 20910
1	Dr. Kenneth O. Hartman Hercules Aerospace Division Hercules Incorporated P.O. Box 210 Cumberland, MD 21502	1	Professor J. D. Achenbach Northwestern University Dept. of Civil Engineering Evanston, IL 60201
1	Dr. Thor L. Smith IBM Research Lab 042.282 San Jose, CA 95193	1	Dr. N. L. Basdekas Office of Naval Research Mechanics Program, Code 432 Arlington, VA 22217
		1	Professor Kenneth Kuo Pennsylvania State Univ. Dept. of Mechanical Engineering University Park, PA 16802

DISTRIBUTION LIST

	<u>No. Copies</u>		<u>No. Copies</u>
Dr. S. Sheffield Sandia Laboratories Division 2513 P.O. Box 5800 Albuquerque, NM 87185	1	ONR Resident Representative Ohio State University Res. Ctr. 1314 Kinnear Road Columbus, OH 43212	1
Dr. M. Farber Space Sciences, Inc. 135 Maple Avenue Monrovia, CA 91016	1		
Dr. Y. M. Gupta SRI International 333 Ravenswood Avenue Menlo Park, CA 94025	1		
Mr. M. Hill SRI International 333 Ravenswood Avenue Menlo Park, CA 94025	1		
Professor Richard A. Schapery Texas A&M Univ. Dept of Civil Engineering College Station, TX 77843	1		
Dr. Stephen Swanson Univ. of Utah Dept. of Mech. & Industrial Engineering MEB 3008 Salt Lake City, UT 84112	1		
Mr. J. D. Byrd Thiokol Corp. Huntsville Huntsville Div. Huntsville, AL 35807	1		
Professor G. D. Duvall Washington State University Dept. of Physics Pullman, WA 99163	1		
Prof. T. Dickinson Washington State University Dept. of Physics Pullman, WA 99163	1		

END

FILMED

4-84

DTIC